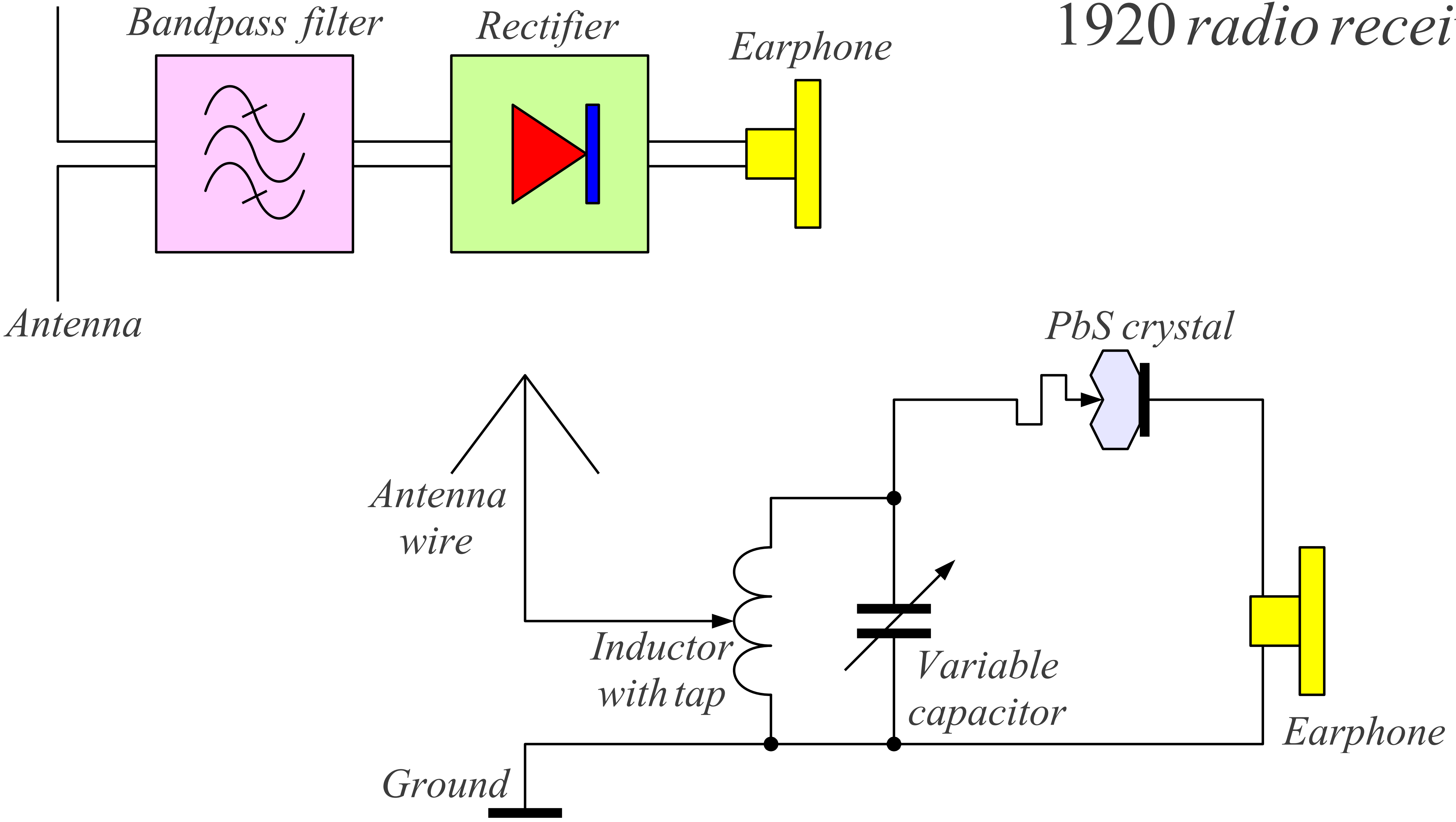
Communication Electronics

Lecture 5:

Semiconductor devices for communications - diodes

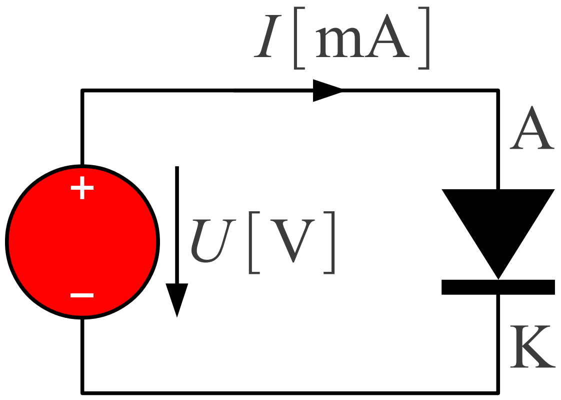
1920 radio receiver



Material	Bandgap ΔW[eV]	Dielectric strength E_{max}[V/cm]	Electron mobility μ_n[cm^2/Vs]	Hole mobility μ_p[cm^2/Vs]
PbS	0.37	(U_{BR}<2V)	600	200
Se	1.95	(U_{BR}<25V)	0.005	0.14
PbSe	0.27		900	700
PbTe	0.32		1700	930
Cu_2O	2.137	(U_{BR}<8V)	0.2	0.1
Si	1.11	$3 \cdot 10^5$	1400	450
Ge	0.67	10^5	3900	1900
$Si_{1-x}Ge_x$		$3 \cdot 10^5$		
SiO_2	9	10^6-10^7		
Si_3N_4	5.4	$3 \cdot 10^6$		
C(diamond)	5.5	10^6-10^7	2200	1800
3C-SiC	2.36	10^6	800	320
4H-SiC	3.23	$3\text{-}5 \cdot 10^6$	900	120
6H-SiC	3.05	$3\text{-}5 \cdot 10^6$	400	90
GaAs	1.43	$4 \cdot 10^5$	5000	400

Semiconductors

Material	Bandgap ΔW[eV]	Dielectric strength E_{max}[V/cm]	Electron mobility μ_n[cm^2/Vs]	Hole mobility μ_p[cm^2/Vs]
AlAs	2.16	$6 \cdot 10^5$	1200	420
InP	1.344	$5 \cdot 10^5$	5400	200
GaP	2.26	10^6	250	150
GaSb	0.726	50000	3000	1000
InAs	0.354	40000	40000	400
$In_{1-x}Ga_xAs$	0.35-1.43			
InSb	0.17	1000	77000	850
GaN	3.4	$5 \cdot 10^6$	1800	30
AlN	6.28	$1.2\text{-}1.8 \cdot 10^6$	300	14
InN	0.65		3200	
BN	5.4	$3\text{-}6 \cdot 10^6$	200	500
CdS	2.42		400	
CdSe	1.74		650	
CdTe	1.44		1100	100
$Hg_{1-x}Cd_xTe$	0-1.5			

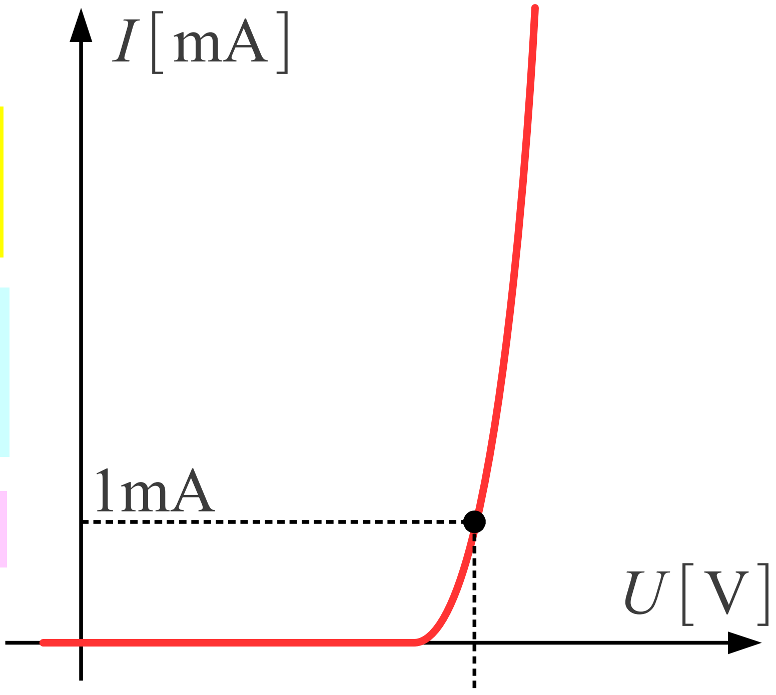


Diode equation

$$I = I_S\left(e^{\frac{U|Q_e|}{n k_B T}} - 1\right) = I_S\left(e^{\frac{U}{n U_T}} - 1\right)$$

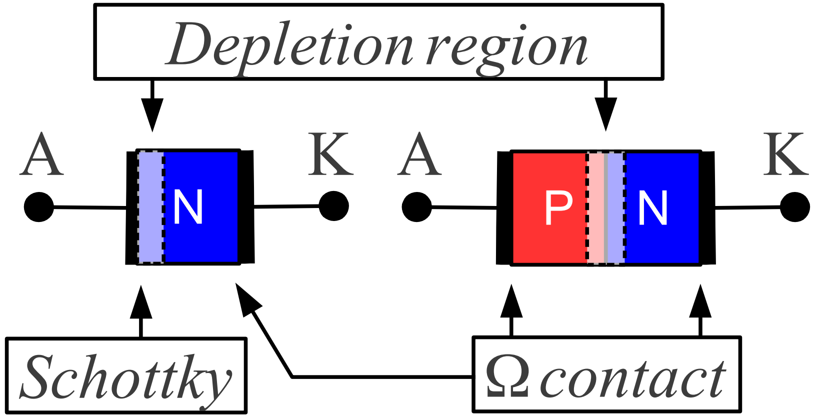
$$\frac{k_B T}{|Q_e|} = U_T \approx 25\,\mathrm{mV} \equiv \textit{thermal voltage}$$

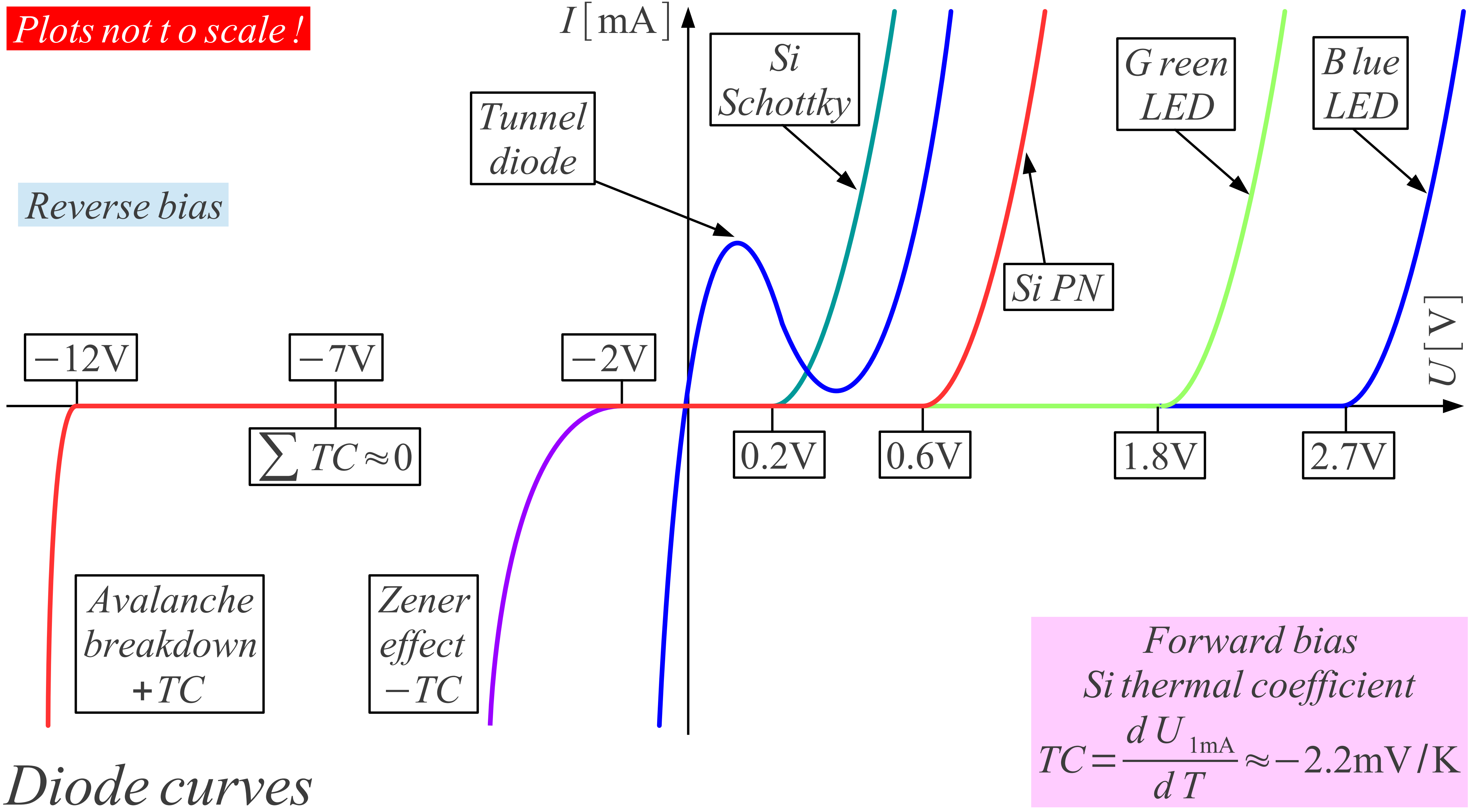
$$1\,(\textit{Si Schottky}) \le n \le 2\,(\textit{Si PIN}) \equiv \textit{diode ideality factor}$$



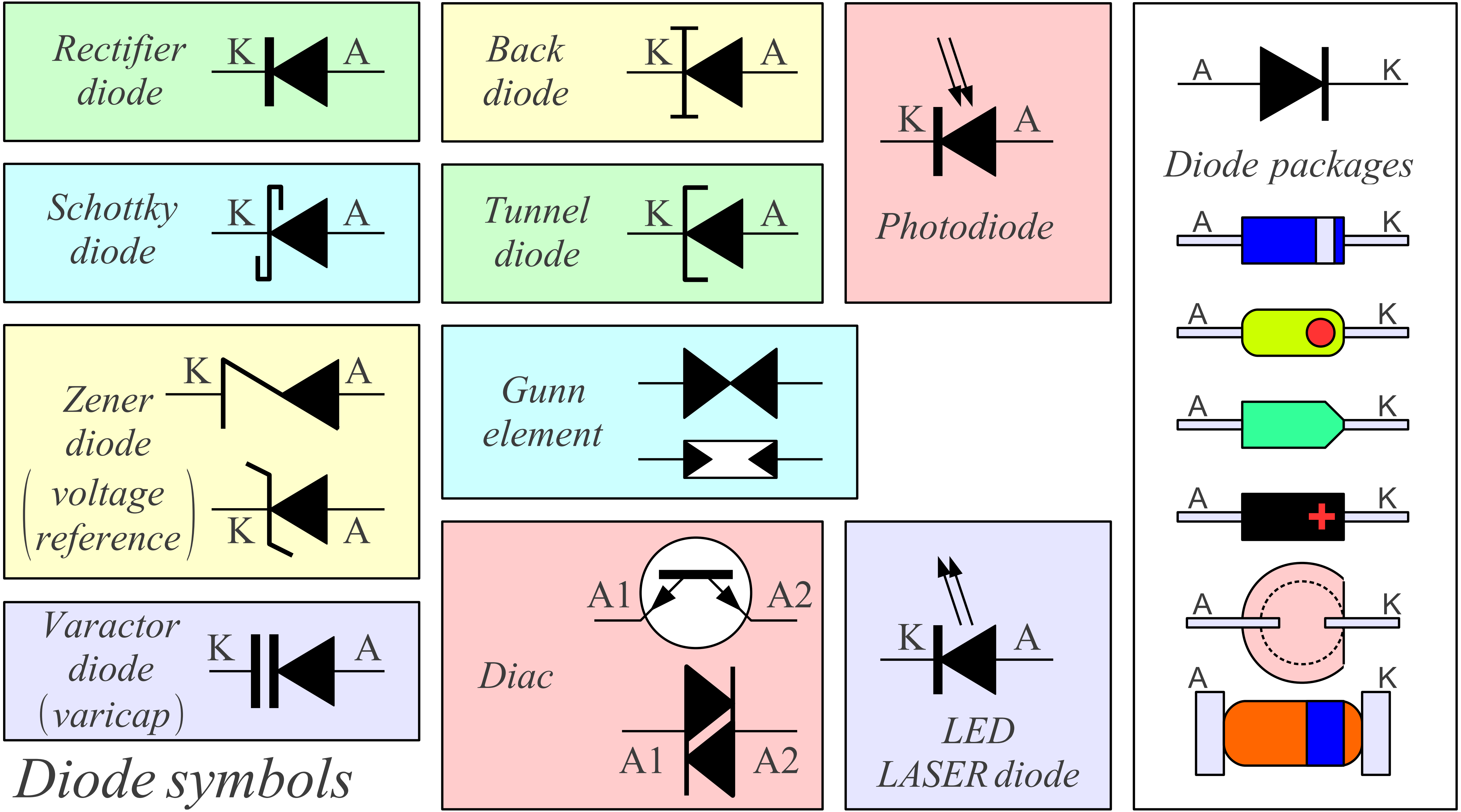
$$PN: \quad U_{1mA} \approx \Delta W[\mathrm{eV}] - 0.4\mathrm{V}$$

Diode type	Semiconductor	ΔW	U_{1mA}	I_S
PN junction	Si	1.11eV	0.5-0.7V	$4 \cdot 10^{-12}$-$2 \cdot 10^{-15}$A
PN junction	Ge	0.67eV	0.1-0.2V	$2 \cdot 10^{-5}$-$4 \cdot 10^{-7}$A
IR LED	GaAs	1.43eV	1V	~$2 \cdot 10^{-20}$A
Green LED	GaP	2.26eV	1.8V	~10^{-33}A
Blue LED	GaN	3.4eV	2.7V	~10^{-48}A
Schottky	Si	1.11eV	0.1-0.4V	$2 \cdot 10^{-5}$-$2 \cdot 10^{-10}$A
Schottky	GaAs	1.43eV	0.7V	~$2 \cdot 10^{-15}$A
Schottky	GaN	3.4eV	1.6V	~$2 \cdot 10^{-30}$A





Plots not to scale !
I [mA]
Reverse bias
Tunnel diode
Si Schottky
Si PN
Green LED
Blue LED
U [V]
−12V
−7V
−2V
∑ TC ≈ 0
0.2V
0.6V
1.8V
2.7V
Avalanche breakdown +TC
Zener effect −TC
Forward bias
Si thermal coefficient
$TC = \frac{dU_{1mA}}{dT} \approx -2.2mV/K$
Diode curves

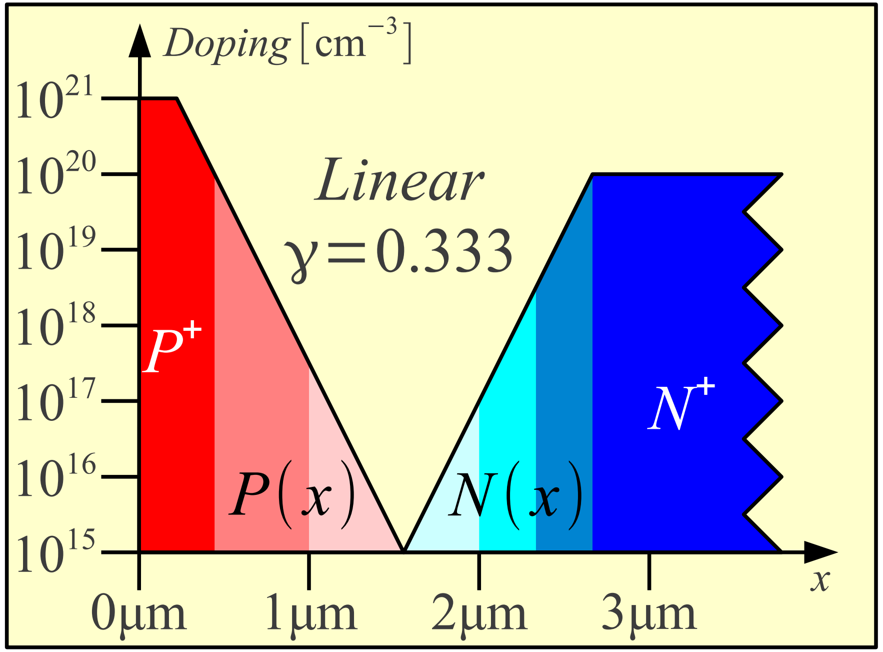


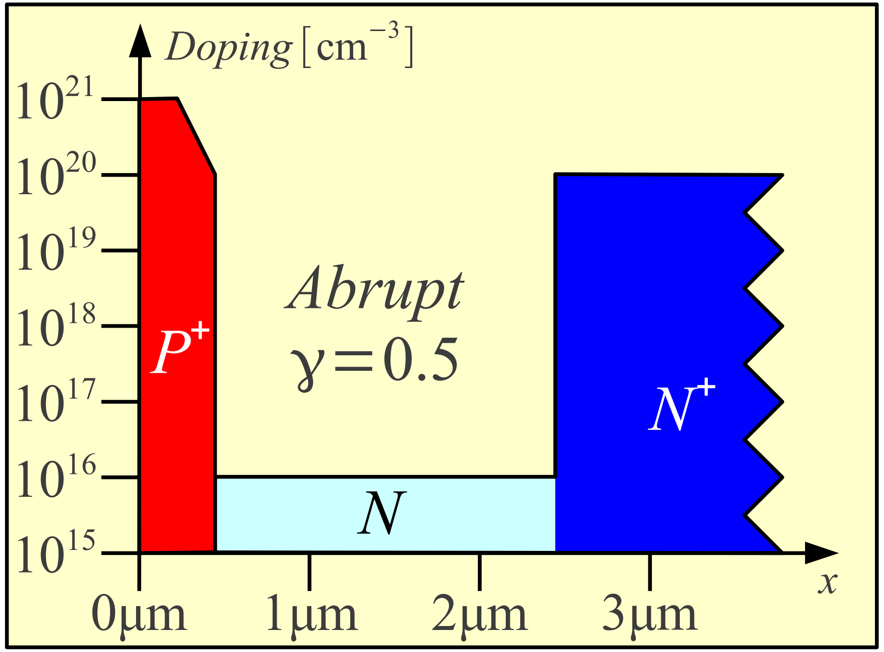
Rectifier diode
K
A
Back diode
K
A
Photodiode
K
A
Diode packages
A
K
Schottky diode
K
A
Tunnel diode
K
A
Zener diode (voltage reference)
K
A
K
A
Gunn element
Varactor diode (varicap)
K
A
Diac
A1
A2
A1
A2
LED
LASER diode
K
A
Diode symbols

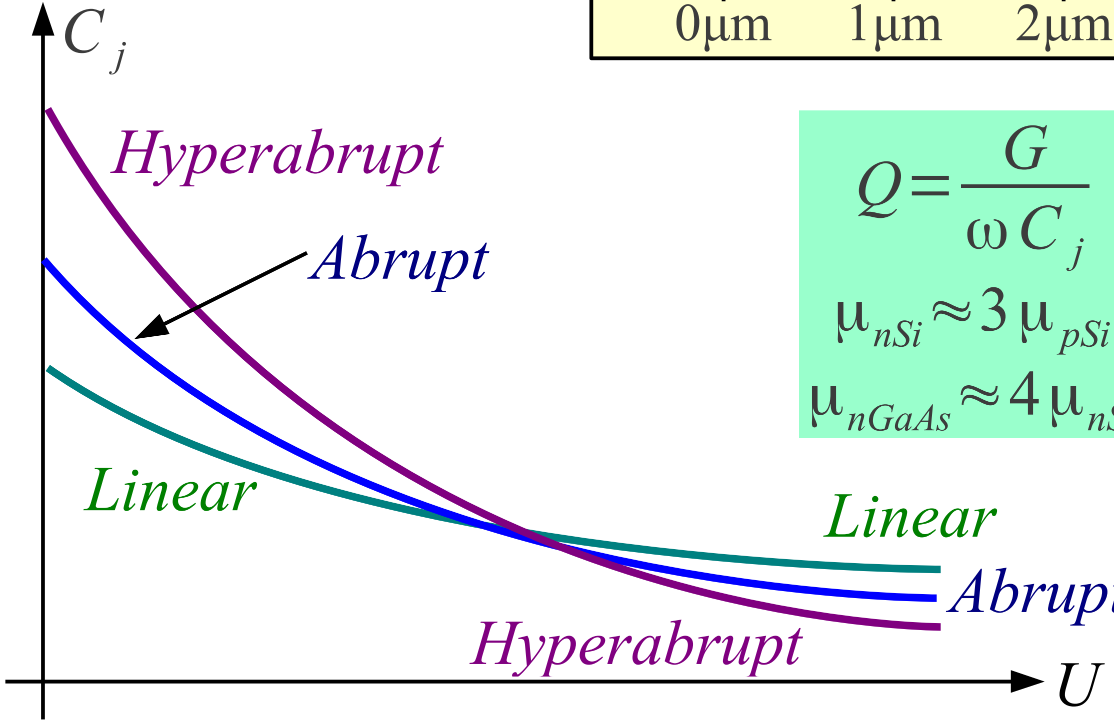
Varactor doping

$$\frac{C_1}{C_2}=\left(\frac{U_1+\phi}{U_2+\phi}\right)^{-\gamma}$$

$\phi_{Si}\approx 0.7\text{V}$



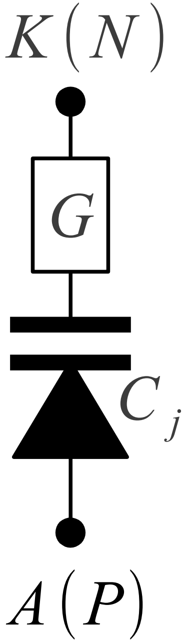


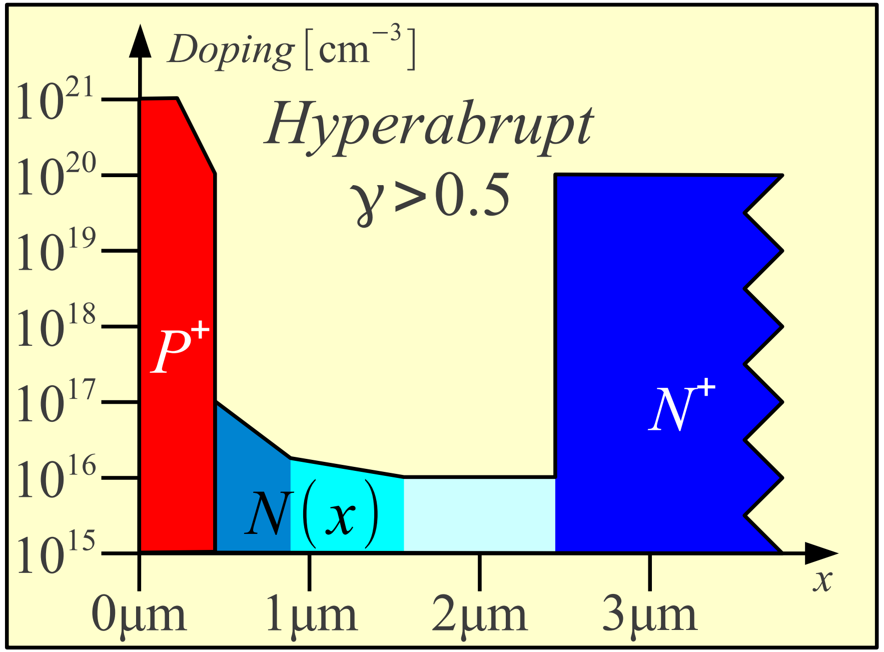


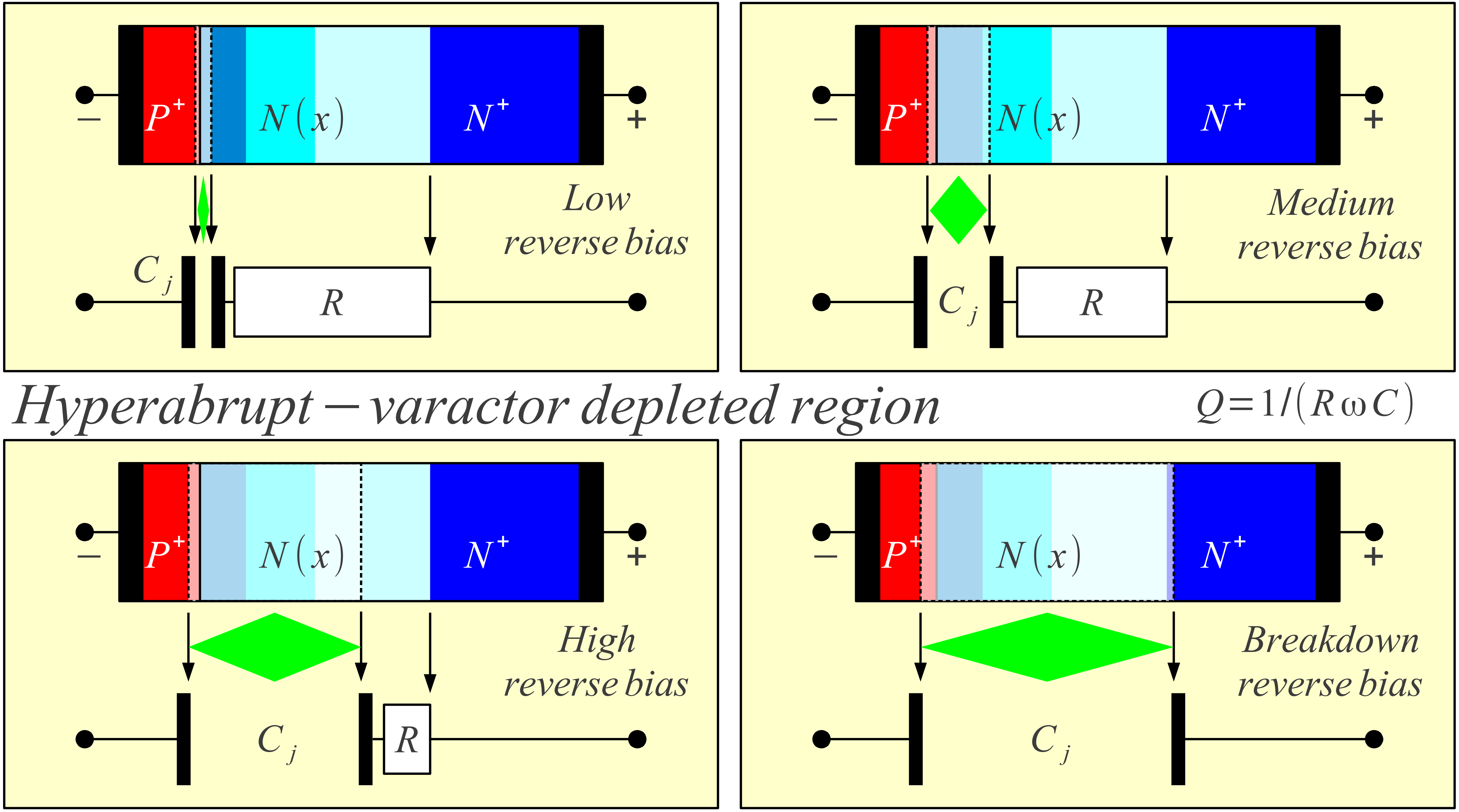
$$Q=\frac{G}{\omega C_j}$$

$\mu_{nSi}\approx 3\mu_{pSi}$

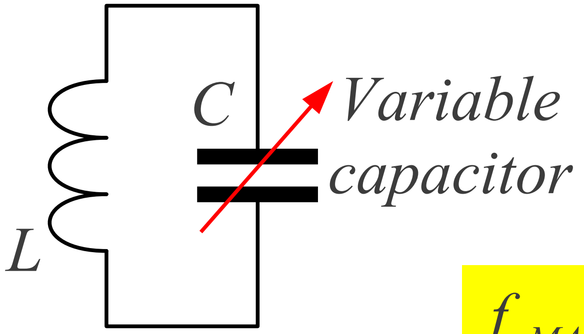
$\mu_{nGaAs}\approx 4\mu_{nSi}$





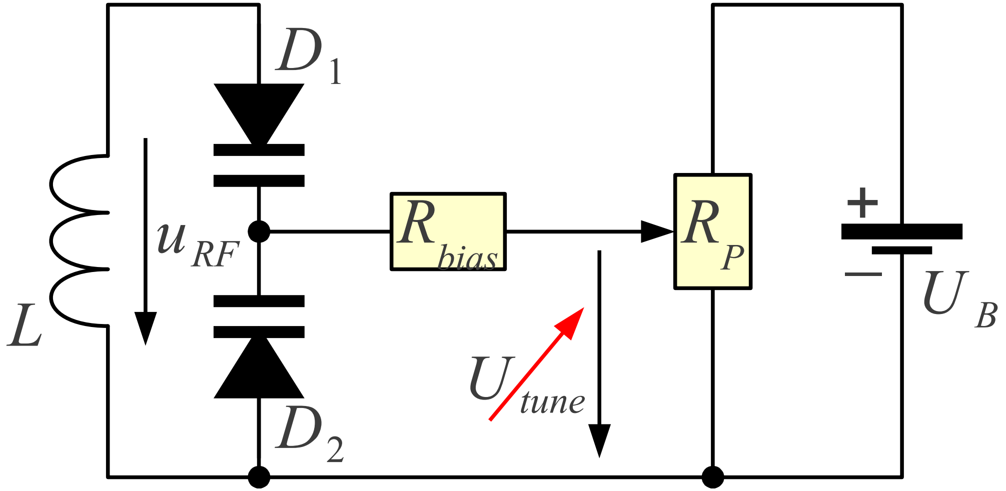


P^+
$N(x)$
N^+
−
+
C_j
R
Low reverse bias
Medium reverse bias
Hyperabrupt − varactor depleted region
$Q = 1/(R\omega C)$
High reverse bias
Breakdown reverse bias

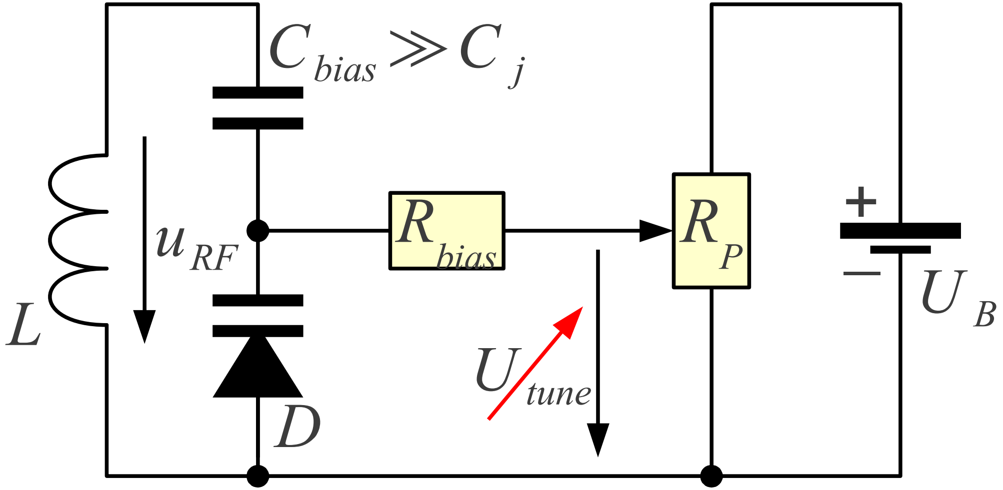


$$f=\frac{1}{2\pi\sqrt{LC}}$$

$$\frac{f_{MAX}}{f_{MIN}}=\left(\frac{C_{MAX}}{C_{MIN}}\right)^{0.5}=\sqrt{\frac{C_{MAX}}{C_{MIN}}}$$



Dual − varactor tuning



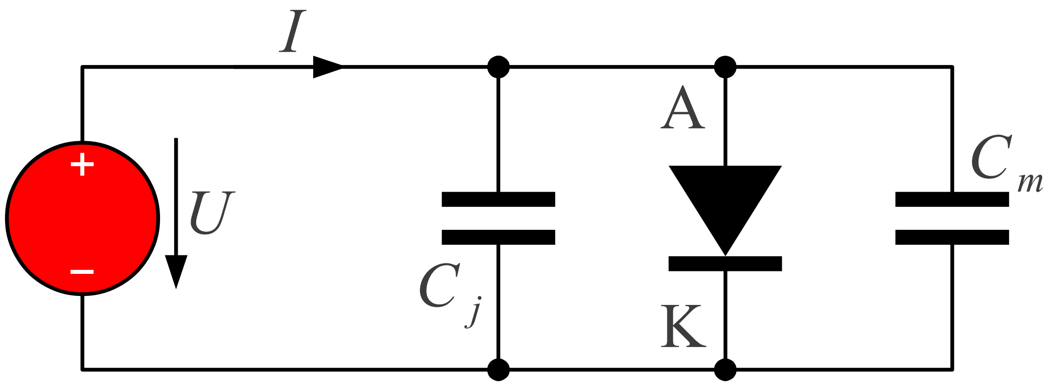
Single − varactor tuning

$$u_{D1}\approx U_{tune}-\frac{u_{RF}}{2} \quad \rightarrow \quad \Delta C_1\approx-\alpha\frac{u_{RF}}{2}$$

$$u_{D2}\approx U_{tune}+\frac{u_{RF}}{2} \qquad\qquad \Delta C_2\approx+\alpha\frac{u_{RF}}{2}$$

$$u_D=u_{RF}+U_{tune} \rightarrow \Delta C_j=\alpha u_{RF}$$

Varactor tuning



$$Q_m \approx \tau I \qquad \tau \equiv minority-carrier\ lifetime$$

$$C_m = \frac{dQ}{dU} = \tau \frac{dI}{dU} = \tau G_d = \frac{\tau I}{n U_T}$$

$$Y_d = \frac{1}{Z_d} = G_d + j\omega (C_j + C_m)$$

$$I = I_S \left(e^{\frac{U}{n U_T}} - 1 \right)$$

$$G_d = \frac{dI}{dU} = \frac{1}{n U_T} I_S \left(e^{\frac{U}{n U_T}} - 1 \right) = \frac{I}{n U_T}$$

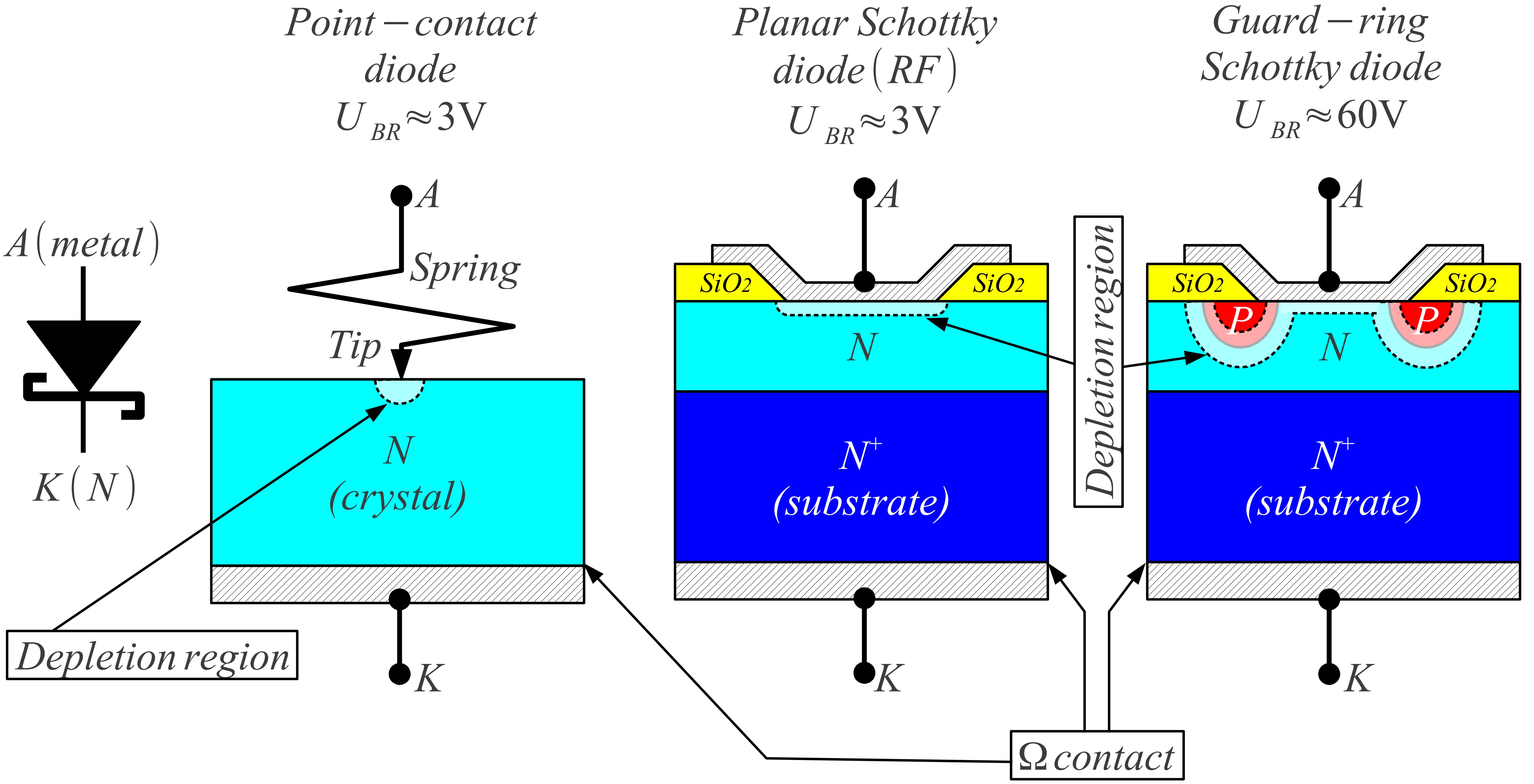
$$R_d = \frac{dU}{dI} = \frac{n U_T}{I}$$

$$I = 1\mathrm{mA} \qquad n U_T \approx 40\mathrm{mV} \rightarrow R_d \approx 40\,\Omega$$

Diode	C_j	τ	C_m @1mA	Z_d @100MHz
1N4007 (PN)	30pF	10μs	250nF	−j6.4mΩ
BAR81 (PIN)	0.3pF	100ns	2.5nF	−j0.64Ω
1N4148 (PN+Au)	4pF	5ns	125pF	(3.5−j11)Ω

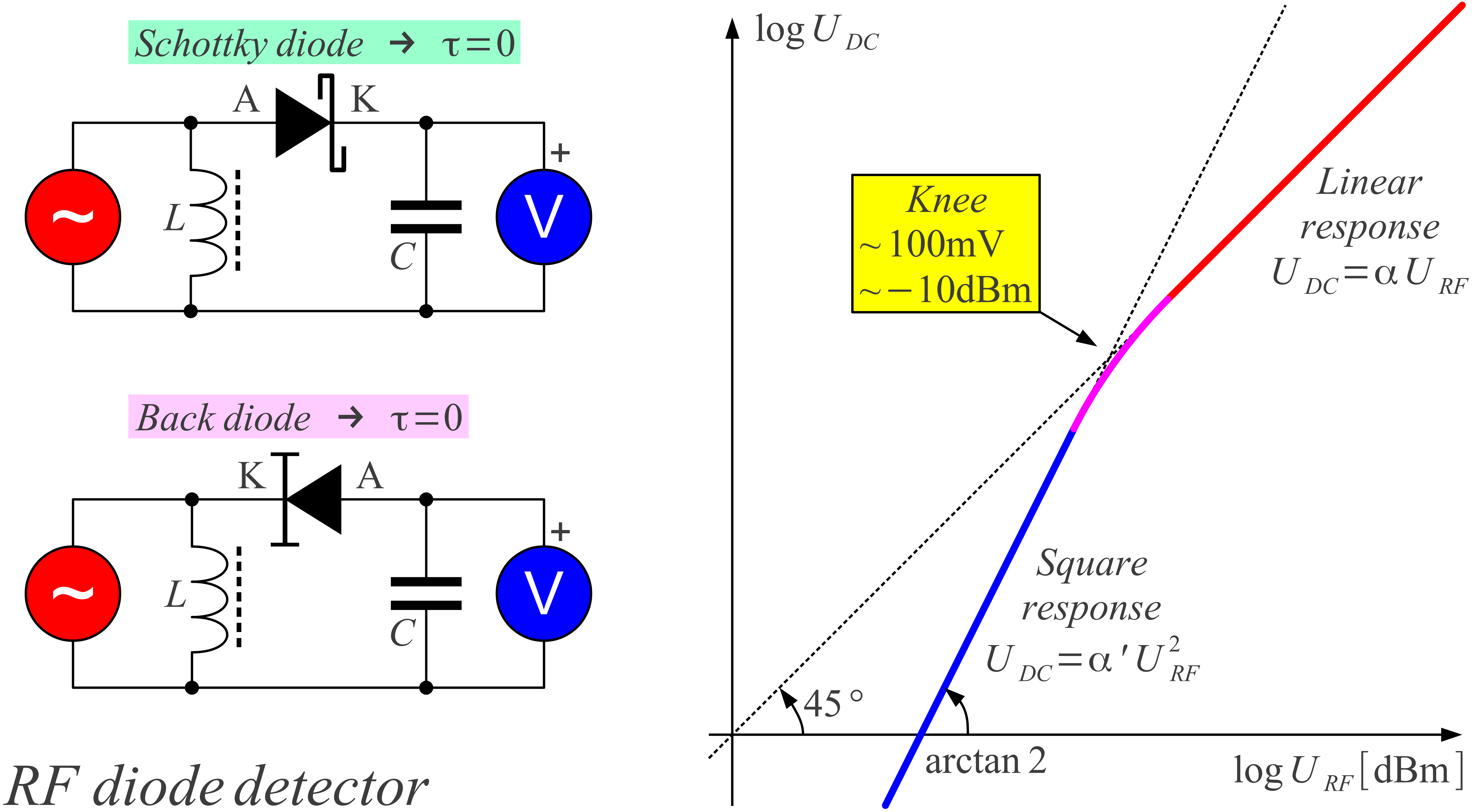
Diode differential admittance

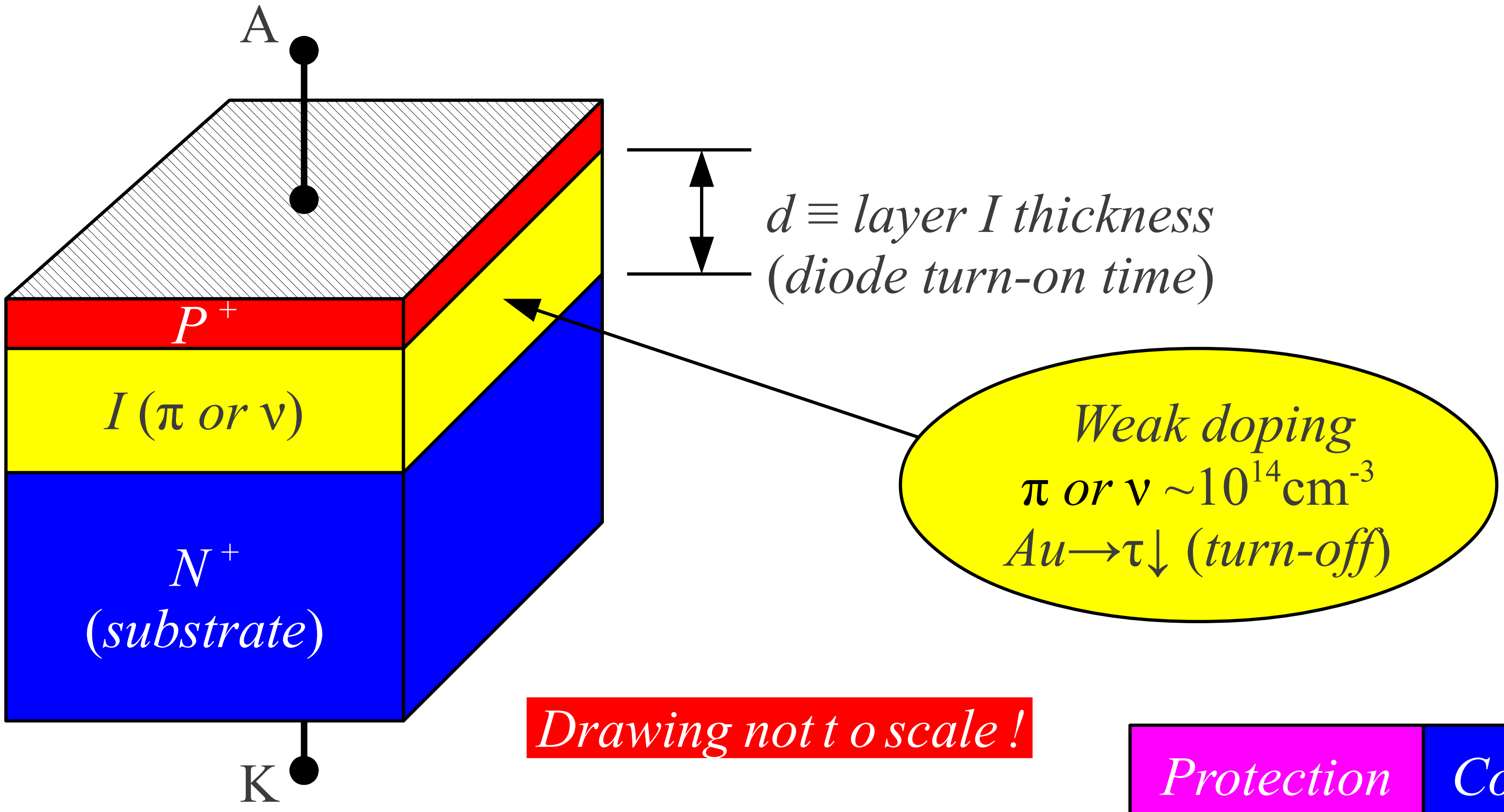
Schottky diode → $\tau = 0$

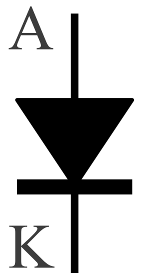


Schottky – diode versions

Drawings not to scale !

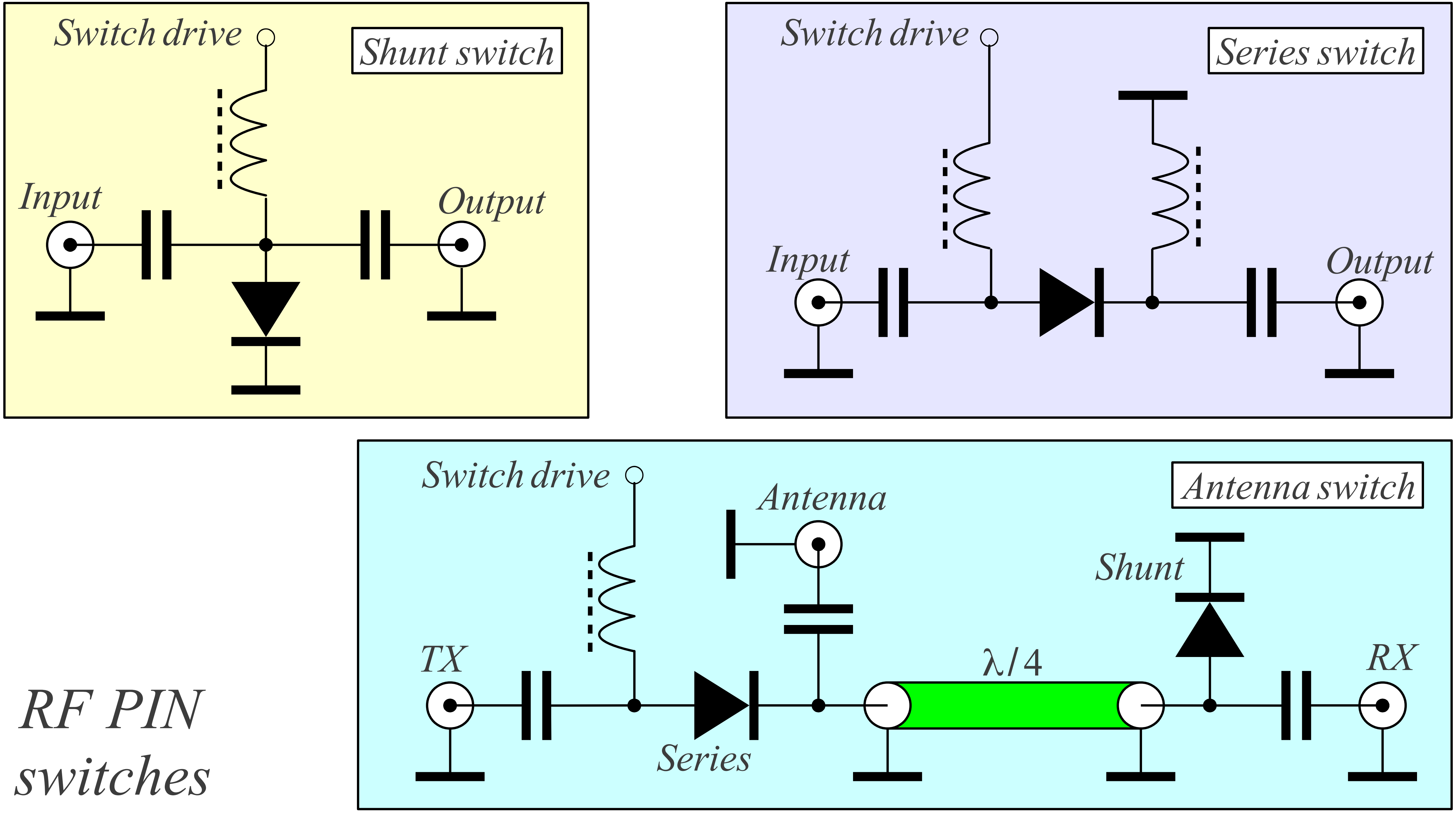

Schottky diode → τ=0
A
K
L
C
V
+
Back diode → τ=0
K
A
L
C
V
+
RF diode detector
log U DC
Knee
~100mV
~−10dBm
Linear response
U DC=α U RF
Square response
U DC=α' U 2 RF
45°
arctan 2
log U RF [dBm]





	Protection limiter	*Controlled RF switch*	*Adjustable RF resistor*
Layer I thickness d	~0.3µm	~3µm	~60µm
Minority-carrier lifetime τ	~10ns	~100ns	~1µs

PIN diodes

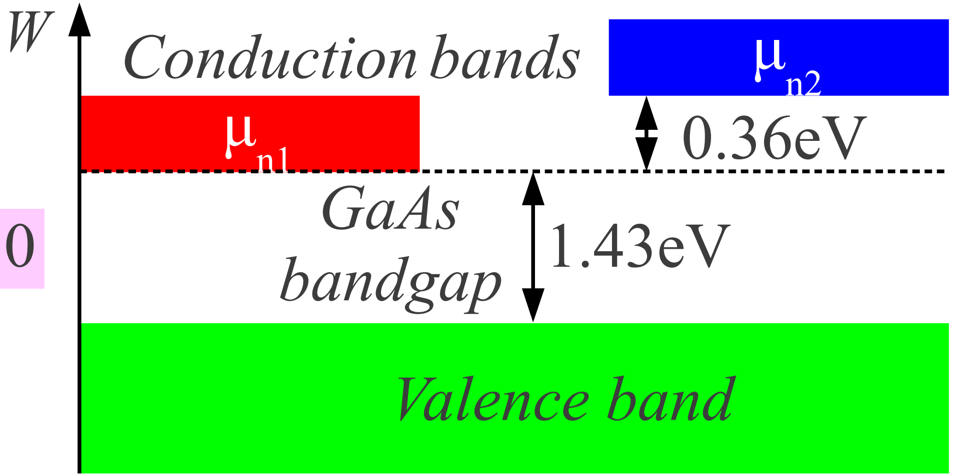


Shunt switch
Switch drive
Input
Output
Series switch
Switch drive
Input
Output
Antenna switch
Switch drive
Antenna
Shunt
TX
λ/4
RX
Series
RF PIN switches

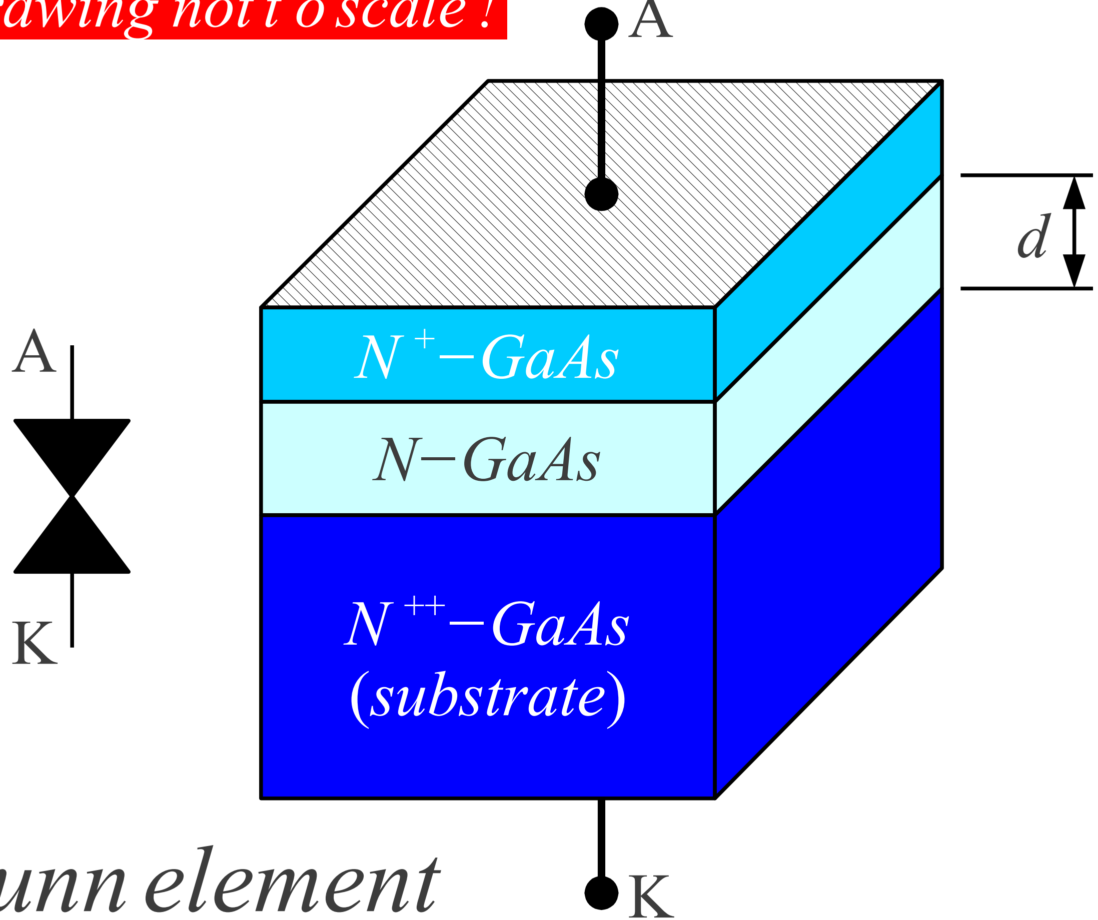
TED ≡ transferred − electron device

GaAs , InP , GaN , CdTe ,
CdS , InAs , InSb , ZnSe ,
bulk semiconductor effect !

$\mu_{n2} < \mu_{n1} \rightarrow R_d < 0$

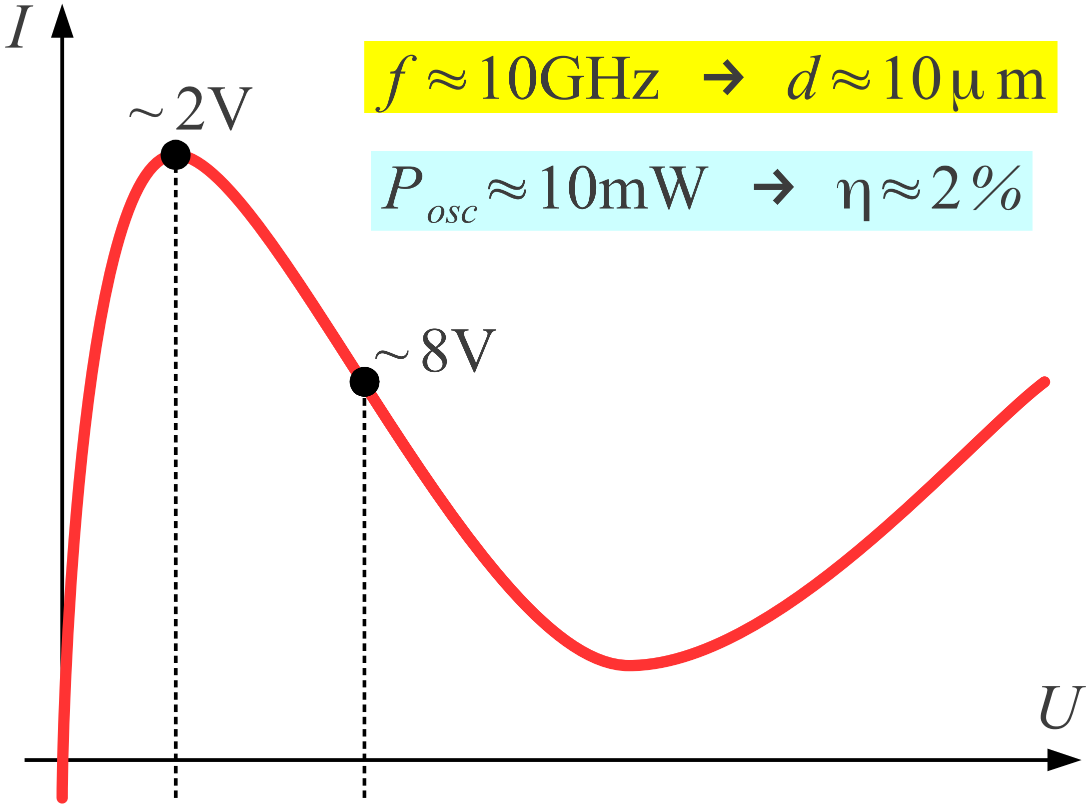


Drawing not to scale !

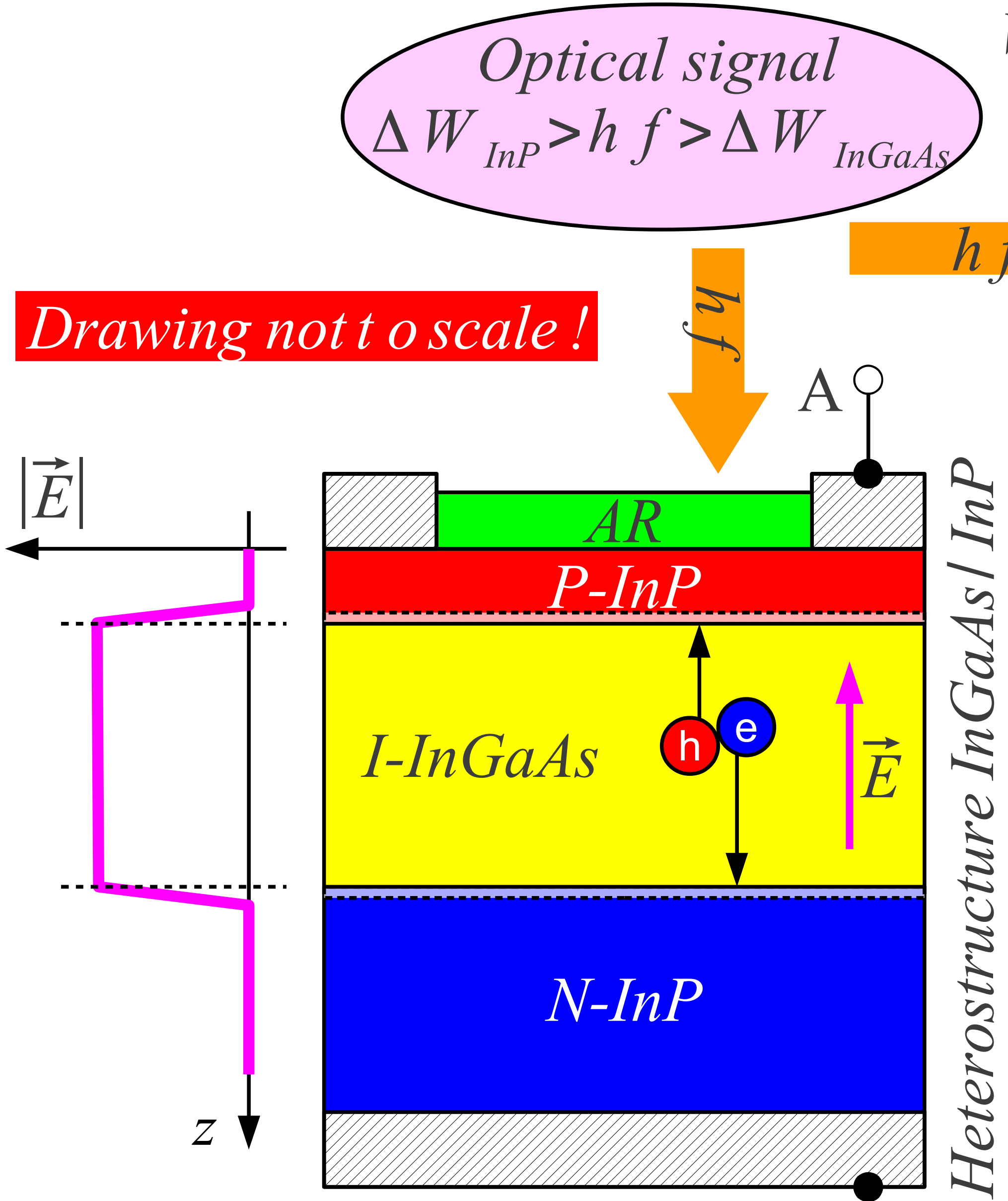


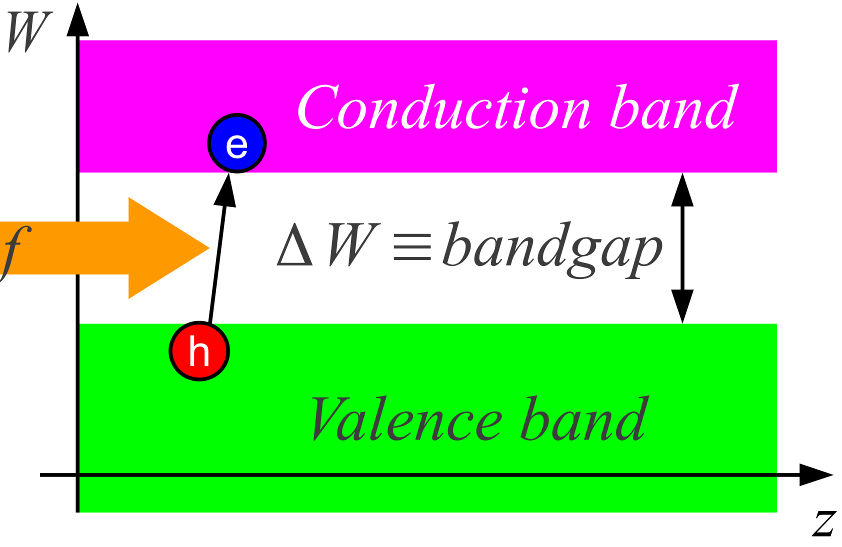
$f \approx 10\text{GHz} \rightarrow d \approx 10\,\mu\text{m}$

$P_{osc} \approx 10\text{mW} \rightarrow \eta \approx 2\%$

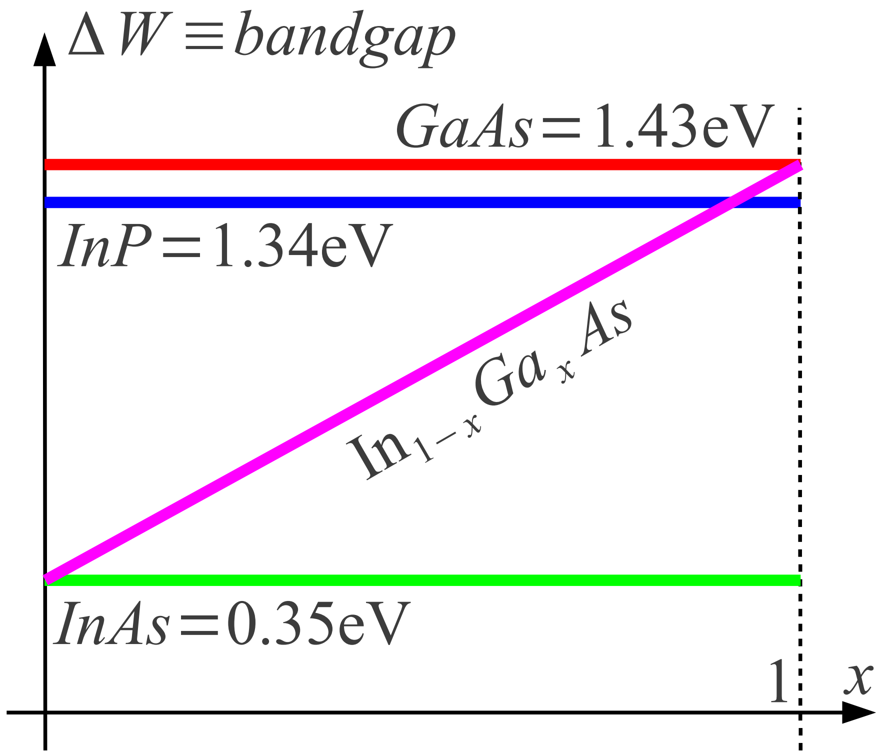


Gunn element





$hc_0 \approx 1.24 \mathrm{eV\,\mu m}$	
λ	hf
0.85µm	1.46eV
1.31µm	0.95eV
1.55µm	0.80eV



$\Delta W \equiv bandgap$
Ge = 0.67eV
$Si = 1.11\mathrm{eV}$
$GaP = 2.26\mathrm{eV}$

Schottky/back rectifier
$\lambda > 0.1\mathrm{mm}$

PN − junction rectifier
$\lambda > 10\mathrm{mm}$

PIN photodiode

Avalanche photodiode

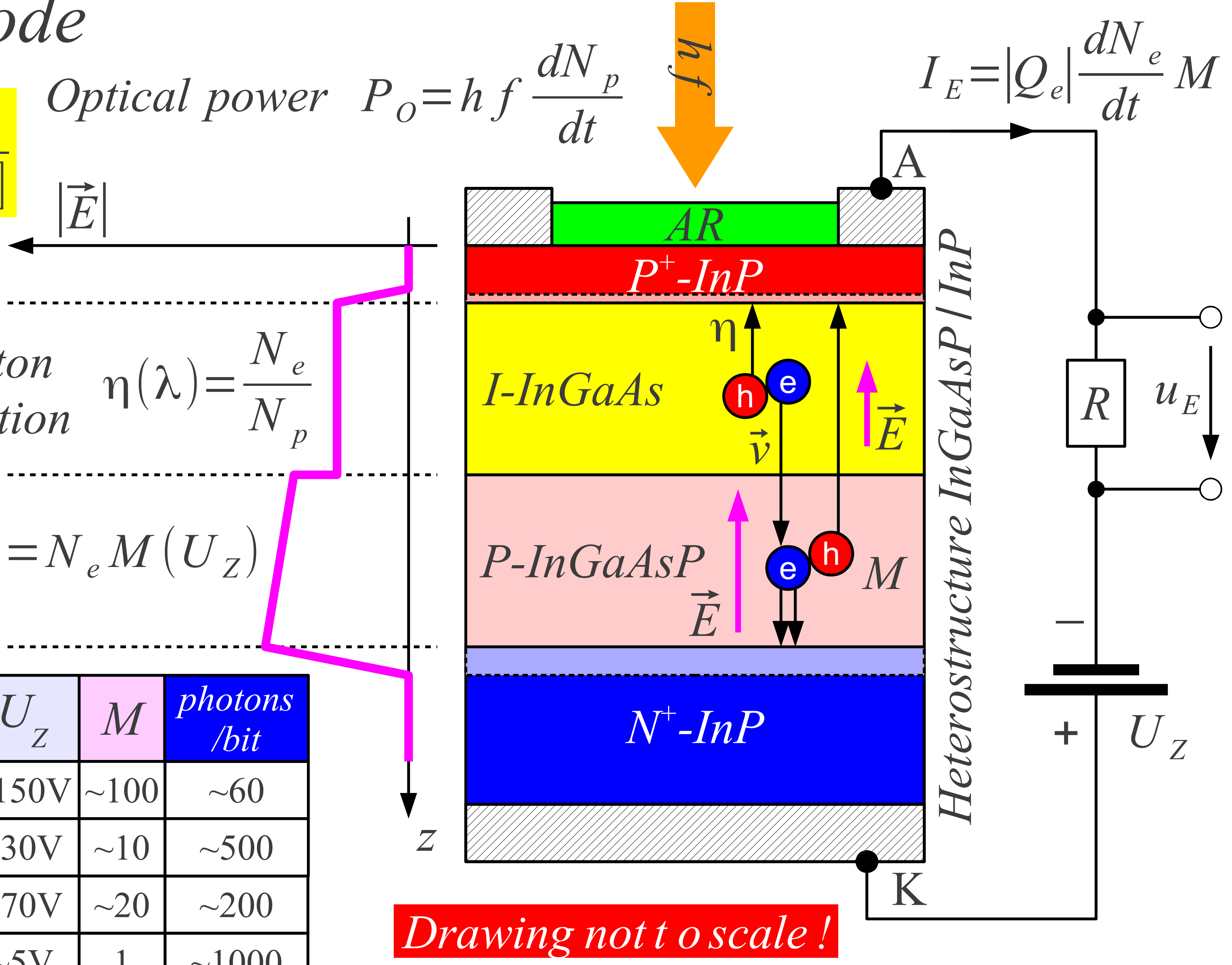
$$\frac{I_E}{P_O}\left[\frac{\mathrm{A}}{\mathrm{W}}\right]=\frac{N_e'|Q_e|}{N_p h f}=\frac{\eta(\lambda) M}{W_p[\mathrm{eV}]}$$

Optical power $P_O = h f \frac{dN_p}{dt}$

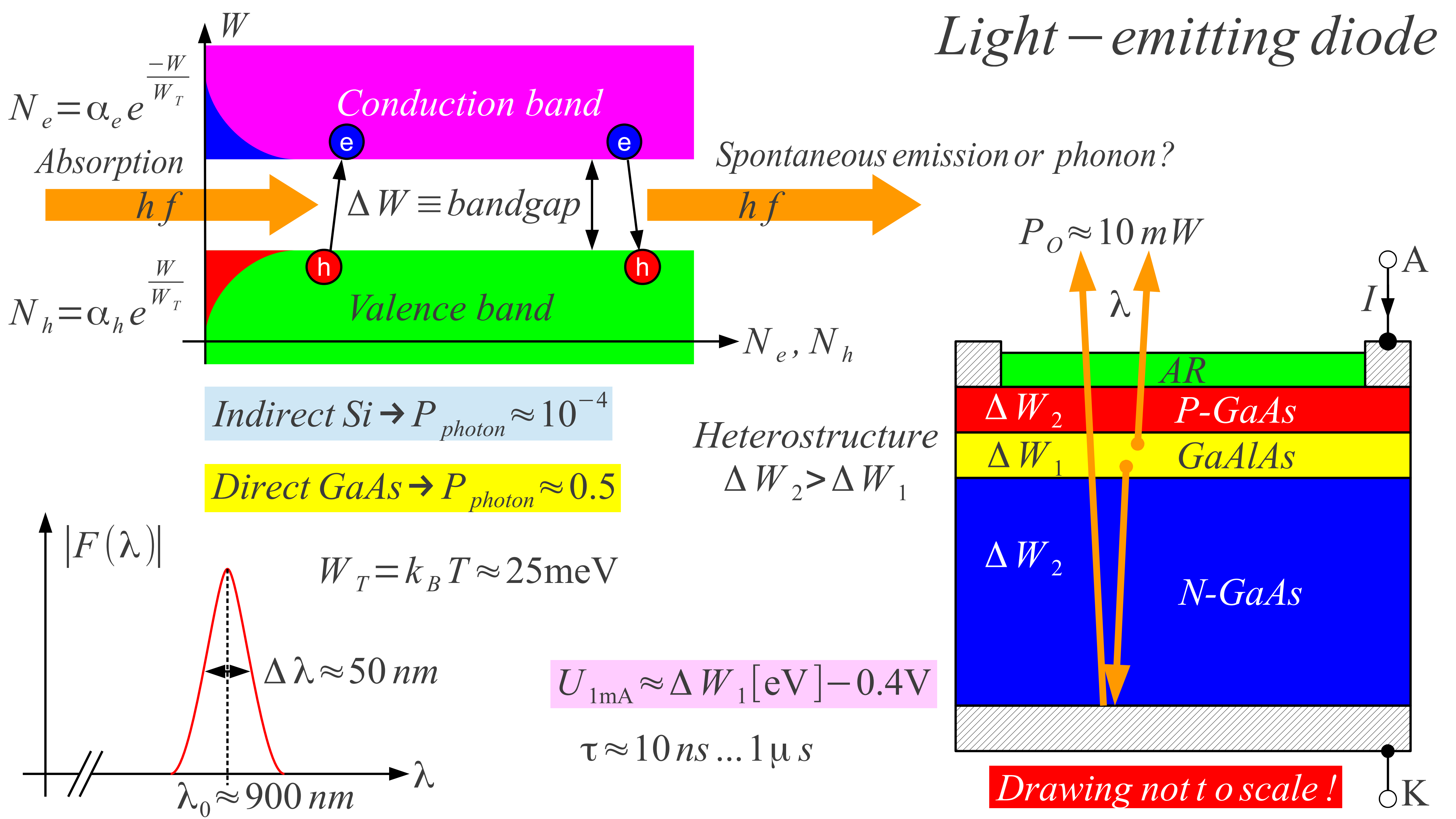
Photon detection $\eta(\lambda)=\frac{N_e}{N_p}$

Electron multiplication $N_e' = N_e M(U_Z)$

$I_E = |Q_e| \frac{dN_e}{dt} M$



APD	ΔW	λ	W_f	U_Z	M	photons /bit
Si	1.11eV	850nm	1.46eV	~150V	~100	~60
Ge	0.67eV	1310nm	0.95eV	~30V	~10	~500
InGaAsP	~0.75eV	1550nm	0.80eV	~70V	~20	~200
PIN	~0.75eV	1550nm	0.80eV	~5V	1	~1000



Light – emitting diode
W
$N_e = \alpha_e e^{\frac{-W}{W_T}}$
Conduction band
e
e
Absorption
Spontaneous emission or phonon?
hf
$\Delta W \equiv bandgap$
hf
$P_O \approx 10\,mW$
h
h
$N_h = \alpha_h e^{\frac{W}{W_T}}$
Valence band
λ
A
I
N_e, N_h
AR
ΔW_2
P-GaAs
Indirect Si → $P_{photon} \approx 10^{-4}$
Heterostructure
ΔW_1
GaAlAs
Direct GaAs → $P_{photon} \approx 0.5$
$\Delta W_2 > \Delta W_1$
$|F(\lambda)|$
ΔW_2
$W_T = k_B T \approx 25\text{meV}$
N-GaAs
$\Delta\lambda \approx 50\,nm$
$U_{1mA} \approx \Delta W_1[\text{eV}] - 0.4\text{V}$
$\tau \approx 10\,ns \ldots 1\,\mu s$
λ
$\lambda_0 \approx 900\,nm$
Drawing not to scale!
K

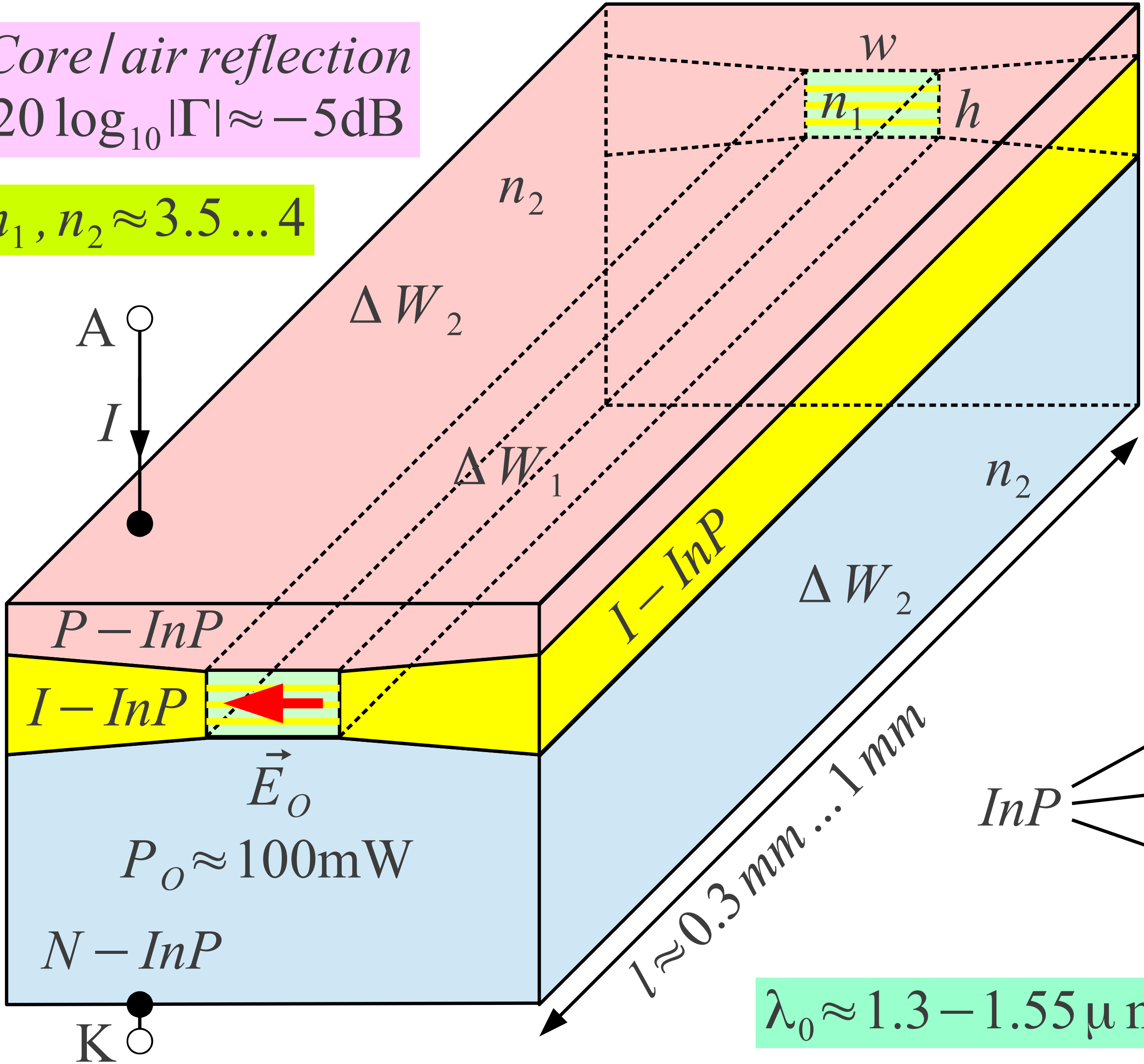
Semiconductor laser

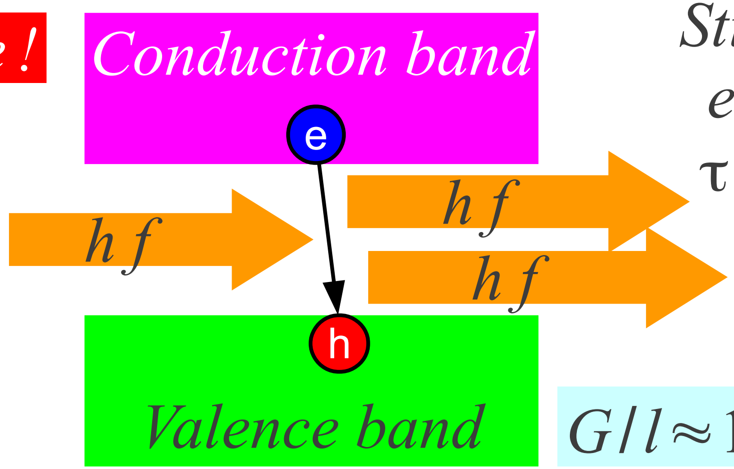
Drawing not to scale!

Core/air reflection

$20\log_{10}|\Gamma| \approx -5\text{dB}$

$n_1, n_2 \approx 3.5 \ldots 4$





Stimulated emission

$\tau \approx 200\text{ps}$

$G/l \approx 10^4\ \text{dB/m}$

Dielectric waveguide $n_1 > n_2$

Avoid cladding loss $\Delta W_1 < \Delta W_2$

$w \approx 10\mu\text{m} \rightarrow$ *single transversal mode*

MQW ≡ Multiple Quantum Well

many layers 10nm … 100nm *thick*

$\lambda_0 \approx 1.3 - 1.55\mu\text{m}$